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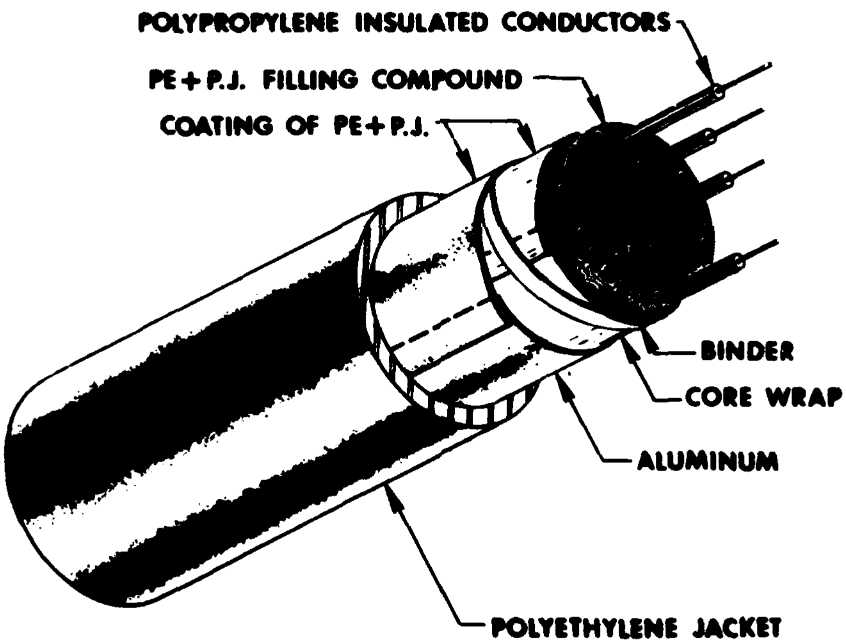

BELL TELEPHONE LABORATORIES, INCORPORATED

SEVENTEENTH ANNUAL WIRE AND CABLE SYMPOSIUM
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ABSTRACT

A waterproof plastic insulated multipair cable for long, buried, rural telephone subscriber routes is now under development, ~~at Bell Telephone Laboratories~~. These routes employ cables having small pair counts and coarse gauge size (typically 25 pairs or fewer, 19 and 22 gauge). The sheaths of these cables are susceptible to lightning and physical damage with subsequent transmission degradation (high, unstable loss, noise, and possible corrosion) due to the entrance of water into the cable core, which has a large percentage of air space. In the design under development this air space is filled with a dielectric compound, consisting of polyethylene and petroleum jelly, which prevents liquid water ingress and thus stabilizes the transmission parameters. Capacitance stability on the order of 1% or less has been achieved on experimental samples immersed in water for many weeks. The voice frequency characteristics of this cable, except for inductance, are similar to those of the present dry PIC cable. At higher frequencies (0.15 MHz to 3.15 MHz) crosstalk performance is the same as that in present PIC cable, and loss is about 15% lower. For the small sizes considered, the waterproof cable cost is estimated to be roughly equivalent to that of standard PAP sheathed PIC cable. Other possible cable applications utilizing the waterproof principle are 24 and 26 gauge distribution cable, aluminum conductor cable, and cables to be used for high frequency systems, such as PICTUREPHONE® service or T1 and T2 carrier systems.

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INTRODUCTION

The present plastic insulated telephone cables used to serve rural subscriber areas may be generally characterized by their small size (25 pairs or fewer), coarse gauge (19 or 22) and by the fact that they are buried, nonpressurized systems having sheaths which are susceptible to lightning and physical damage. Such damage leaves the cable core exposed to possible transmission degradation due to the entrance of water into the core structure, which has a large percentage of air space (approximately 47% of the core cross section is air). The transmission degradation takes the form of high, unstable loss, noise, and electrochemical corrosion of the wires and the metallic shield at conductor insulation defects when coupled by water. The insulation defects are the result of manufacturing and installation irregularities essentially impossible to eliminate at reasonable cost.

Because of the air space within the sheath, water which enters the cable at one location may run a long distance, depending on topography, making sheath and pair fault detection and correction extremely difficult. Entrance of such water, with its poor dielectric properties, into the interstitial spaces of the cable core results in an increase in the mutual capacitance of the cable pairs, which in a water-filled cable amounts to an increase of 138% or 2.38 times that of the nominal 0.083 microfarads per mile value for dry cable.[1] This results in an increase of 55% in 1 kHz loss. The capacitance change, together with about a 45 to 1 increase in conductance, results in an even larger increase in high frequency loss, e.g., an increase of approximately 75% at 3 MHz in a water-filled 22 gauge cable. The loss in cables in field use varies anywhere from the nominal dry value to the completely filled value, depending on the amount of water in the core.

One possible solution to this problem is the use of more elaborate lightning resistant and mechanically robust sheath structures. This solution is expensive, since in small cables such sheaths increase the cable cost substantially. Furthermore, the use of the more expensive sheaths

fails to solve the problem of accidental entry of water at leaky splices or points of sheath damage. As already noted, location and removal of water, once it has entered a PIC cable core, is a formidable undertaking.

A more economical solution to the problem, which is now in the development stage, consists of filling the air spaces among the insulated conductors with a suitable dielectric compound having good electrical, mechanical, and water resistance characteristics. This approach 1) prevents liquid water ingress in the presence of a sheath break, 2) stabilizes electrical transmission, 3) permits use of an economical sheath design, and 4) prevents water from flowing along the cable length. The localization of water entry greatly simplifies and facilitates repair of pair faults and sheath damage.

The merit of the four advantages is dramatized in a simple demonstration illustrated in Figure 1. Water poured into a sheath "fault" in standard PIC cable runs freely out the ends, demonstrating the water pipe effect due to the air space. Water poured into a similar "fault" in waterproof cable is completely restrained.

WATERPROOF DESIGN

Figure 2 shows a sketch of the waterproof cable design now under field trial. The conductors are insulated with polypropylene having the standard color code and are twisted with the standard twist-length scheme. The insulated twisted pairs are completely encapsulated in a dielectric filling compound which consists basically of 15% low density polyethylene and 85% petroleum jelly. The filled core is covered with a longitudinally applied core wrap of mylar or polypropylene bound with helical servings of oriented polypropylene ribbon.

The waterproof core is protected with a modified alpeth sheath. The chief functions of the sheath are 1) protection of the filled core from physical damage, 2) interception of lightning, 3) control of noise, and 4) protection of the aluminum shield from corrosion. The modifications of the standard alpeth sheath consist simply of compound floodings between the aluminum and the core and between the aluminum and the external polyethylene jacket. The resultant cable structure is thus completely filled, with no axial flow paths for water to enter. The coating over the aluminum is used to prevent longitudinal flow, seal the overlap, and provide a form of corrosion resistance. The merit of

eliminating the water path between the aluminum and the core is self-evident in stabilizing the electrical characteristics of the cable. Figure 3 shows a photograph of the filled cable with the pairs fanned out.

FILLING COMPOUND

The filling compound is the heart of the waterproof cable design concept. Such a compound must satisfy several requirements. Some of these are 1) water resistance, 2) good dielectric properties, 3) low cost, 4) favorable high and low temperature properties, and 5) favorable handling characteristics (minimum greasiness and stickiness). Thus, the field of potential filling candidates narrows very quickly. A material which satisfies most of these requirements is petroleum jelly. It is water resistant and, except for the lowest grades, has good dielectric properties ($\varepsilon \simeq 2.2$, $\tan\delta \simeq 0.0001$). It is also very attractive economically.

However, petroleum jelly has two characteristics which are judged to be unfavorable. The first is its consistency. Petroleum jelly is soft and greasy and wets the skin easily. It also melts and flows at fairly low temperatures, with typical melting points of about 120°F - 135°F. The first characteristic would evoke unfavorable craftsman reaction, while the second would result in compound flow in hot environments, such as exposure to direct sunlight in reel storage areas or along routes prior to placement or even in pedestal terminals which are exposed to the hot sun.

A near optimum filling compound capable of meeting all of the design requirements is achieved by blending low density polyethylene into petroleum jelly, in the ratio of 15 parts PE to 85 parts P.J. The resultant compound essentially retains the low cost of petroleum jelly, is a nongreasy, pastelike material, and does not flow except at well above any possible ambient. It wets the conductor insulation well enough to prevent interfacial penetration of water and is soft enough to adjust to the movement of the core conductors during handling at low or high temperatures without channeling and without causing appreciable stiffness of the final cable. The use of the preferred blend and the method of blending represent a major breakthrough in the development of the waterproof concept.[2] Addition of an appropriate antioxidant assures retention of the desirable properties for many years.

ELECTRICAL DESIGN CRITERIA

One of the design criteria for the waterproof cable is that of maintaining the present cable capacitance of 0.083 microfarads per mile and also the same dc resistance. Maintaining

the same dc resistance requires only that the wire diameters remain unchanged. However, some compensation must be made in order to maintain the present capacitance, since the filling compound with an $\varepsilon \simeq 2.2$ replaces air with $\varepsilon = 1$. Figure 4 shows a cross section of air core and filled core PIC cable represented simply as a single shielded balanced pair for illustration purposes.

At the bottom of the figure is the equation for the mutual capacitance between the wires.[3] Since d, the wire diameter, has been fixed, there are only two major ways of compensating for the increased capacitance due to the filling compound. The first approach is to increase S by enlarging the DOD of the insulated wire. The second approach is to reduce the ε, effective dielectric constant of the cable, e.g., through the use of expanded wire insulation. The first of these two alternatives has been chosen at the present time due to its simplicity and short development schedules. The second approach, expanded insulation, is being evaluated as the next step in achieving a more economical design. Figure 4 shows $\varepsilon \simeq 1.80$ for air core PIC and $\varepsilon \simeq 2.23$ for waterproof PIC. A 22 gauge cable with solid insulation requires a DOD increase from 44 mils to 53.5 mils, assuming a constant S/D ratio, in order to maintain 0.083 microfarads per mile in the waterproof design.

WIRE INSULATING MATERIAL

Standard PIC cable used in the Bell System is made with low density, high molecular weight polyethylene insulation on the conductors. In the waterproof cable, polypropylene rather than polyethylene insulation is used over the conductors. The decision for this change was made on the basis of results of a series of accelerated tests at elevated temperatures. Tensile tests on plastic micro-tensile samples and wire wrap tests on insulated wire samples aged in intimate contact with petroleum jelly show that petroleum jelly greatly reduces the tensile strength of polyethylene and causes the insulation on wrapped insulated wires to tear and break loose from the wire. These tests immediately raised doubts about the long-term mechanical aging performance of polyethylene insulated wires which have been exposed to petroleum jelly or petroleum jelly blends and which must be handled periodically at terminals. Under similar test conditions polypropylene samples have performed significantly better than polyethylene and have not failed the wire wrap test.

WATER IMMERSION TESTS

Several types of water immersion test were devised in order to evaluate the performance of filled cable samples.

Figure 5 shows the various procedures used. In each of the first three illustrations holes were placed in the aluminum shield and plastic jacket of the samples, usually at about 1-foot intervals. This was done to accelerate the tests by making sure that the water could get to the filled core immediately. In all tests capacitance measurements were used to detect any water ingress. Measurements of other properties , such as high frequency loss, insulation resistance and conductance, were made in specific tests or on specific samples.

Figure 5(A) shows a small water bath used mostly to screen many of the early design variations and to provide quick checks on small sample lengths. The cylindrical tank shown in Figure 5(B) is used for lengths of about 30 feet. The pond immersion test illustrated in Figure 5(C) is used for immersing whole reel lengths at the Chester Laboratory. A typical pond test employed about 300 feet of loosely wound cable at a depth of about 6 feet, with holes placed in the sheath at frequent intervals. The vertical water tests illustrated in Figure 5(D) are used to evaluate interfacial effects between the various cable components and also the quality of the filling immediately above and below the core wrap. As would be expected, inadequate filling permits a small amount of water to find its way along the length of the cable. The tank is drained and the cable ends allowed to dry to permit capacitance measurements which assess the degree of penetration of water into the core.

Results of the tests illustrated in Figures 5(A) and 5(B) have shown the ability to make samples with capacitance stability on the order of 1% or less after several weeks of water immersion. The more severe pond test has shown, in the first long manufactured length, the need for good filling immediately above and below the core wrap, so that the cross section under the aluminum shield is completely filled. This was indicated by an average capacitance increase of only about 1% to 1.5% for pairs in the innermost layers, while an average increase of about 6% was observed on pairs in the outer layer of the single unit 3-layer core. Similar results were obtained in the vertical water tests of Figure 5(D). However, modifications in the filling procedure on the manufacturing line have considerably improved the filling over the core wrap, and both the vertical water test and the tank tests confirm this improvement with capacitance stability equal to or less than 1% throughout the core structure. Pond immersion tests on this later cable are now under way. Another test length with sheath holes and closely spaced conductor insulation defects on several

pairs has been buried in a swampy section of the Chester Laboratory with a 45V dc potential on all the pairs, for long aging performance studies and transmission measurements.

MECHANICAL TESTS

Bending tests have been made on several filled cable samples in order to determine the effect, if any, on the filled core. These tests have been made at room temperature and several other points down to -30°F. Basically the tests consist of bending the cable several times about a drum with a diameter 10 times that of the cable. Visual inspection of the cable cores and electrical evaluations of the samples were made after bending. The electrical tests consist of capacitance monitoring of water immersed samples. Results of both evaluations show no signs of channeling, parting, or any similar type of degradation of the filled core and no problems with cable stiffness, although the cable is somewhat stiffer at the very cold temperatures than at room temperature.

Wire wrap tests on polypropylene insulated wires have been made at -30°F and have shown no degradation in the insulation. Samples aged in air and in intimate contact with the filling compound have shown no noticeable difference.

Plowing tests have also been made on filled cable samples at the Chester Laboratory. A standard plowing routine, consisting of normal and hard starts, turns, and raising and lowering of the plowshare while in motion and at rest was employed. During the plowing operation wire and shield continuity was monitored, while capacitance and insulation resistance measurements were made before and after the plowing operation. In addition, several plowed samples were removed from the earth by manual digging. Some of these samples were cut apart and visually inspected, while others underwent water immersion tests. All of the testing and inspections showed that the filled samples came through the plowing routine very well with only the normal (in present PIC cable) slight decrease in capacitance during installation. The average capacitance increase after several weeks in water was less than 1%.

COMPOUND FLOW TESTS

As discussed previously, one of the benefits derived from the polyethylene-petroleum jelly blend is the fact that the high temperature flow point is considerably higher than that of the petroleum jelly alone. This protects against the possibility of compound flow in hot weather before installation or at above-ground pedestals. A simple test procedure

used to evaluate this property is shown in Fig. 6. Short samples with the ends flared slightly so that pairs are separated are suspended vertically in an oven at 80°C with the flared ends down. After many weeks in this environment cable samples showed no signs of flowing or dripping.

Another aspect of the flow properties of the filling compound at high temperatures has been determined from experience gained in blending the materials to form the compound. It was discovered that fast, uniform cooling of the hot mix is required to attain a material with good high temperature flow properties. Room temperature cooling of the hot mix in a large container results in quite different high temperature flow properties than quick cooling in a small container. Cooling rate tests show that cooling of this compound in the cable core does provide the fast, uniform cooling desired with the method developed for filling during manufacture.

SPLICING TESTS

Several short cable lengths have been spliced by a telephone company craftsman in the laboratory to evaluate splicing problems associated with the filling compound. It was concluded that there are no serious splicing problems other than some added inconvenience and possibly a longer splicing time. Experience with the field trial cables has confirmed these conclusions.

Because of the increased insulation thickness and the fact that the filler compound might be present on the contact surfaces inside splicing connections, some sample wire joints have been prepared and evaluated using B Wire Connectors. Limited results show that connections made without removing the plastic insulation behaved poorly while those joined with stripped insulation behaved well, with or without the presence of the compound film. This is no penalty however as standard practice requires removal of plastic insulation on 19 and 22 gauge conductors when B Wire Connectors are used.

ELECTRICAL CHARACTERIZATION

Electrical characterization of waterproof cable consists of determining primary and secondary constants, insulation resistance, dielectric strength, capacitance unbalance to ground, and crosstalk performance.

As previously mentioned, the mutual capacitance and dc resistance of this cable are the same as those of present PIC cable, with one important exception. The deviations of capacitance from the design objective are appreciably reduced with the filled cable, compared with standard PIC. The 1 kHz inductance, due to the increased insulation thickness, is about 10% larger than the inductance of present PIC cable. Since voice frequency α (attenuation), β (phase constant), and Z_0 (characteristic impedance) are dependent only upon resistance and capacitance, they are the same as those of present PIC cable.

Table 1 lists some of the average electrical parameters obtained on the first experimental lengths of filled cable (about 1000 feet long). These cables are 25 pair, 22 gauge single unit designs. Also shown for comparison purposes are values obtained on standard 22 gauge PIC cables. Aside from R_{dc}, L, and C, this list also includes 1 kHz conductance and 150 kHz far-end crosstalk. The measured conductance at 1 kHz was 0.06 micromhos per mile versus a range of 0.1 to 0.25 micromhos per mile for standard air core PIC cable. The far-end output-to-output crosstalk is seen to be the same as that for present PIC with a median value of 82.5 dB per mile. Figure 7 shows the far-end crosstalk distribution at 150 kHz of single unit waterproof cable and standard PIC cable of 25 pair, 22 gauge size. Also shown are data on a 25 pair unit of a 100 pair, 22 gauge PIC cable. The data on the standard PIC units are comparable to those obtained on the waterproof cable. Far-end crosstalk at 3 MHz also shows a similar comparison.

The high frequency characteristics of the waterproof cable are shown in Table 2. The values of resistance, inductance, and characteristic impedance were calculated from the measured values of attenuation, phase shift, and capacitance. A fact worthy of note here is the 15% lower high frequency loss of the filled cable compared to standard PIC cable. This is due to its higher impedance and lower ac resistance caused by the thicker plastic wire insulation. The reduced attenuation is an advantage in a cable intended for high frequency applications.

Also measured on the first experimental lengths but not shown in the tables were insulation resistance and capacitance unbalance to ground. The insulation resistance has shown an acceptable level of about 20,000 megohm-miles. The capacitance unbalance to ground varies from about 140 to 165 picofarads/1500 feet. Recent data on present 22 gauge PIC cable also averages in this range. Studies show that the filling compound readily fills insulation defects, with the result that the dielectric strength for conductor to conductor and conductor to sheath

approaches the intrinsic values for polyolefins. Hence, values in excess of several tens of kilovolts should be realized in the field - a distinct advantage in lightning performance.

EXPERIMENTAL CABLE FABRICATION

Experimental cable fabrication progressed from manual stranding and filling with a hot flooding tank for rather short (10-15 feet) early laboratory samples to the use of modified WECo production lines at Omaha. The basic idea of drawing the insulated, twisted pairs through a hot melt tank and forming them together at the exit of the tank was established in the early work in the laboratory. This idea has been applied successfully to several types of production lines at Omaha. Appropriate alterations of standard sheathing lines were made to achieve the desired modified alpeth sheath. Field trial quantities have been fabricated with highly satisfactory results. Details of the factory arrangements are beyond the scope of this paper.

COST ESTIMATES

Initial cost estimates of filled cables in the small size range presently being considered show the cable costs to be roughly equivalent to the PAP sheathed PIC cables presently recommended for buried use. Figure 8 shows a cost comparison between waterproof cable and PAP sheathed PIC cable in the 19 and 22 gauge sizes. As can be seen by the curves, the percentage cost differential between the designs decreases with the cable size. This occurs because the sheath costs assume a larger percentage of total cable cost as the cables become smaller and less filling compound is required. The percentage difference between the curves varies from -1.8% for 11 pair, 22 gauge cable to +7.2% for 25 pair, 19 gauge cable. If filling is extended to finer gauges, estimates show the equivalent cost points for waterproof cable vs PAP sheathed PIC cable to be 16 pair, 24 gauge and 25 pair, 26 gauge. However, reduced maintenance costs and the achievement of transmission stability far outweigh the small initial cost increments for the larger sizes considered.

FIELD TRIALS

Field trials of the waterproof cable are now under way or scheduled in several Bell System Operating Companies. The purpose of the trials is to obtain first hand field feedback on the handling, splicing, installation, repair, and transmission performance of the new design and eventual information on maintenance performance. The trials are planned to obtain a broad range of environmental

conditions and to include a total of about 50 miles of 25 pair, 22 gauge cable. It is planned to monitor various electrical parameters of several pairs in each cable for a period of time in order to observe their performance. Information based on the first installation which was made at Vinton, Iowa early in October has been favorable, although it is still early in the trial stage. Limited commercial production of waterproof cable is expected to begin about the fourth quarter of 1969.

OTHER APPLICATIONS

Considering the Bell System goal of burying all new plant by 1970 and the desire for the utmost in service reliability, there are several other possible buried, filled cable applications which are being considered besides the rural subscriber cables. Some of these candidates are 1) 24 and 26 gauge subscriber distribution cable, 2) aluminum conductor cable, 3) high frequency systems and 4) larger multi-unit cables.

Subscriber distribution cables are highly susceptible to workmen damage from grading and digging. In the past the basic problem with aluminum conductor cable has been wire corrosion caused by moisture. The use of plastic wire insulation and more elaborate double jacket and bonded jacket sheaths has greatly reduced this problem, thus achieving the economies associated with the use of aluminum. However, filling the cable core would truly eliminate the moisture problem and permit the use of a more economical sheath structure. Systems such as PICTUREPHONE® service and digital transmission systems such as T2, which will operate in the low megahertz range, will require extremely good transmission stability. The intercity T2 cables also require gas pressurization and monitoring, which would not be required in a filled cable. As previously mentioned, the lower loss of the filled cable at higher frequencies may also be used to advantage. In initial development work only single unit cables have been evaluated. However, multi-unit filled designs appear feasible and will be considered if economical on an overall system basis.

Having achieved a filled, waterproof cable design, we can now evaluate much of the hardware associated with the buried cable system and consider the possibility of design changes in these areas, which may result in cost savings. We are confident that we are on threshold of a revolution in buried cable technology and that significant innovations in splicing, terminating, access to subscribers and related problems will be stimulated by the availability of the waterproof cable.

SUMMARY

A waterproof plastic insulated telephone cable is now under development at Bell Telephone Laboratories. This cable will be initially used on long, rural subscriber routes where small, coarse gauge cables are now in use. The air space within the core structure of this cable is filled with a PE-P.J. dielectric compound which prevents liquid water ingress in the event that the cable sheath should be penetrated in a wet environment. Water immersion tests on experimental cables with holes in the outer sheaths have shown that it is possible to maintain capacitance to within 1%. Except for inductance, the voice frequency electrical characteristics of this cable are similar to those of the present PIC cable. At high frequencies (0.5 MHz to 3.15 MHz) the loss of the waterproof design is about 15% lower than that in present PIC cable, while crosstalk performance (150 kHz and 3 MHz) is equivalent. Work is continuing on the possibility of using expanded wire insulation in order to reduce the cost of the cable, which for the small sizes is roughly equal to that of PAP sheathed PIC cable.

Besides rural subscriber cables, other cable applications for the waterproofing principle are being considered, such as distribution, aluminum conductor, and high frequency cable systems.

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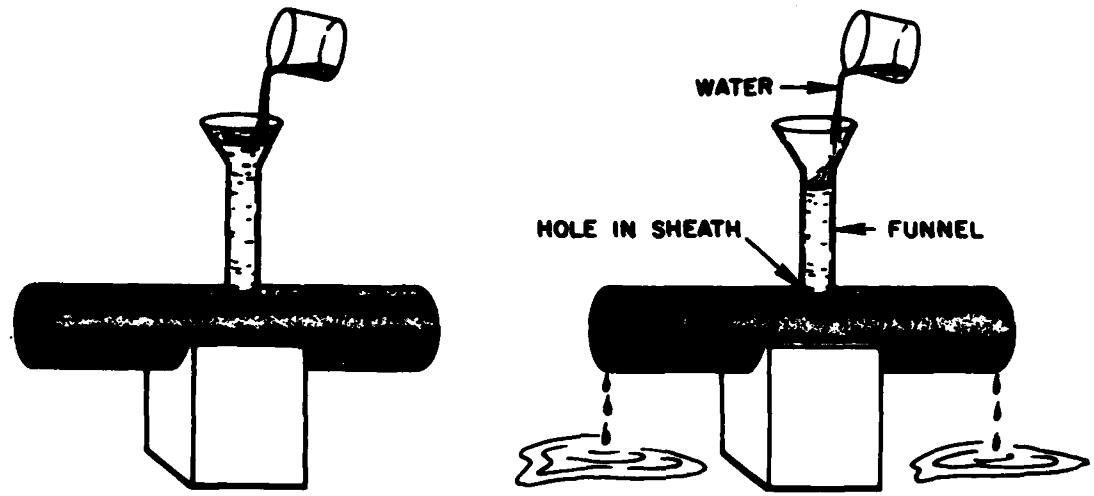
TABLE 1

COMPARISON OF WATERPROOF AND STANDARD PIC CABLES - 22 GAUGE

Measured Characteristics	Waterproof	Standard PIC
DC resistance (72°F) ohms/mile	176.6	175.3[4]
Inductance (1 kHz) mH/mile	1.11	1.00[4]
Capacitance (1 kHz) μF/mile	0.083	0.083[4]
Conductance (1 kHz) μ℧/mile	0.06	0.1-0.25
FEXT (150 kHz) dB/mile	82.5	82.0[5]

TABLE 2

	0.5 MHz		1 MHz		3.15 MHz	
	Waterproof	Std.[6]	Waterproof	Std.[6]	Waterproof	Std.[6]
Attenuation dB/mile (72°F)	15.66	18.45	21.99	26.04	40.07	46.38
Phase Shift Radians/mile	27.95	26.27	55.09	51.28	170.11	157.29
Resistance ohms/mile	384.20	424.60	527.70	584.80	935.10	1012.40
Inductance mH/mile	0.95	0.83	0.92	0.80	0.89	0.76
Impedance ohms	107.20	100.80	105.50	98.20	103.30	95.50

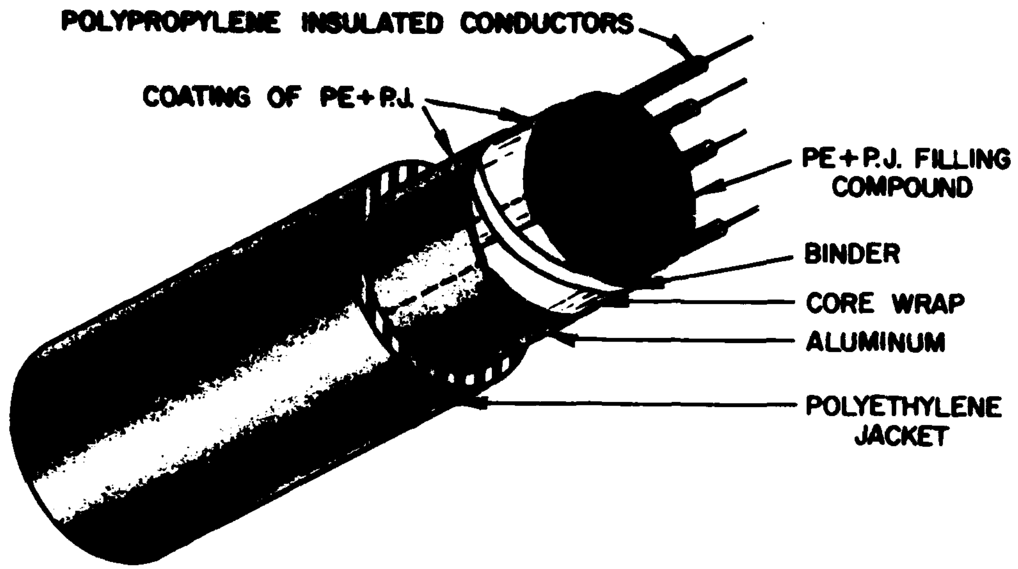


WATERPROOF CABLE

STANDARD PIC CABLE

WATER FLOW DEMONSTRATION

FIG. 1



EXPERIMENTAL WATERPROOF CABLE DESIGN

FIG. 2.

CASE NO. | Bell Telephone Laboratories | PHOTO NO.

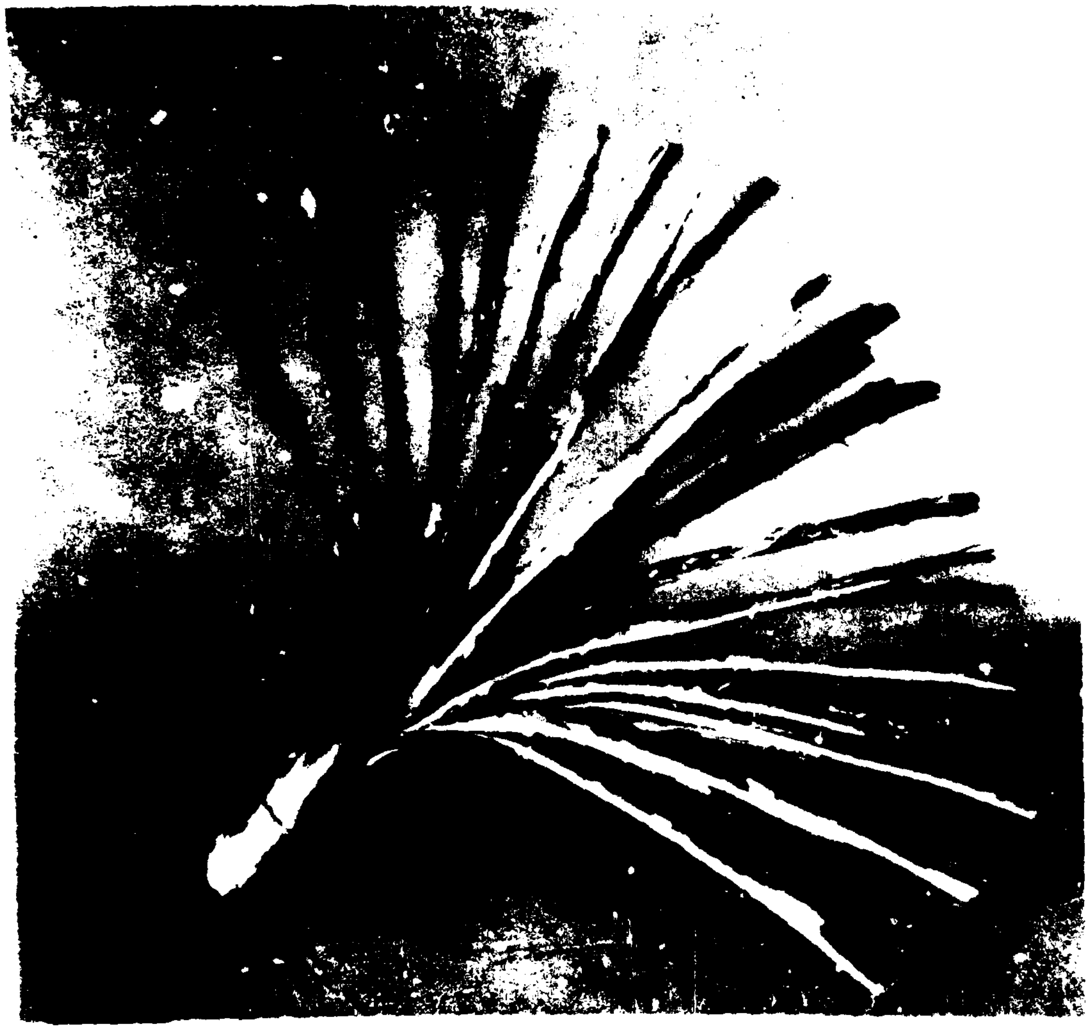
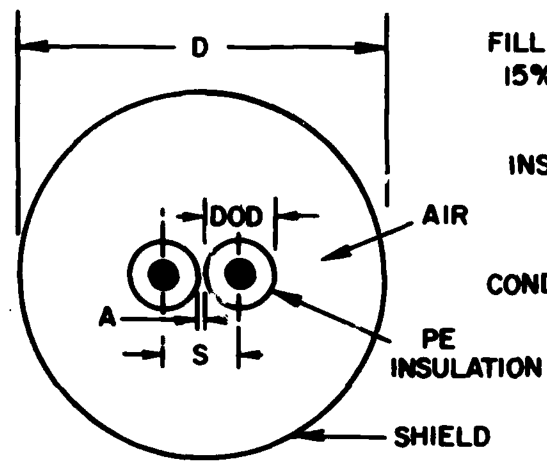


FIGURE 3. WATERPROOF CABLE

AIR CORE PIC

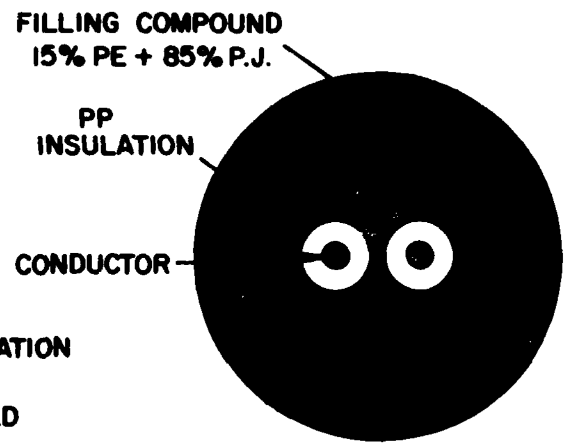


$\epsilon \simeq 1.80$

DOD = 44 MILS — 22 GA.

C_M = .083 μF/MI

WATERPROOF PIC



$\epsilon \simeq 2.23$

DOD = 53.5 MILS — 22 GA.

C_M = .083 μF/MI

$$C_M = \frac{0.01944\,\epsilon}{\mathrm{LOG}_{10}\left(\frac{2S}{d}\,\frac{D^2-S^2}{D^2+S^2}\right) - 0.1086\,\delta_{12}} \quad ; \; S = DOD + A$$

FILLER COMPENSATION

FIG. 4.

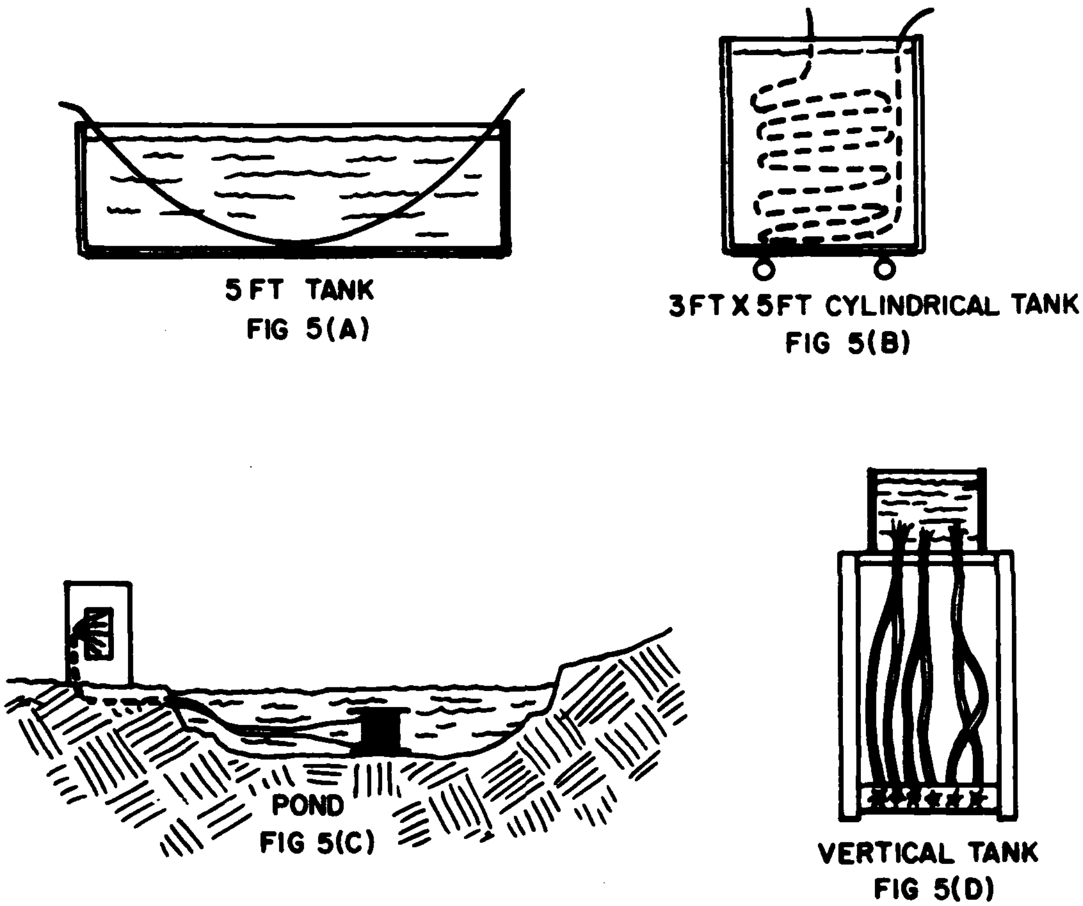
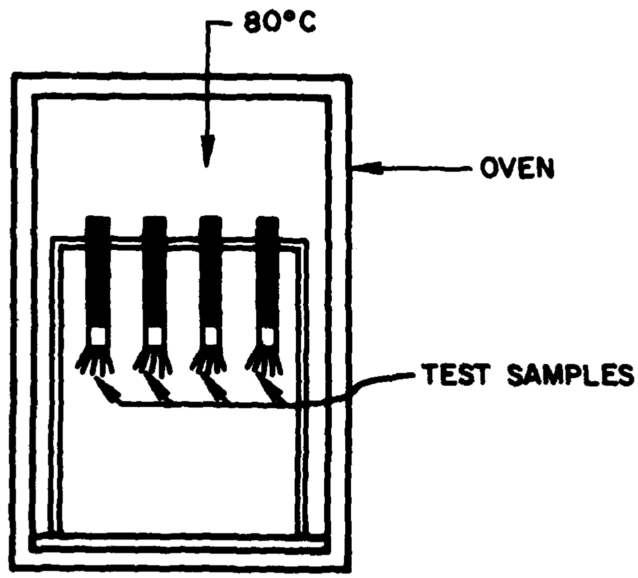


FIGURE 5. WATER IMMERSION TESTS



COMPOUND FLOW TESTS
FIG. 6.

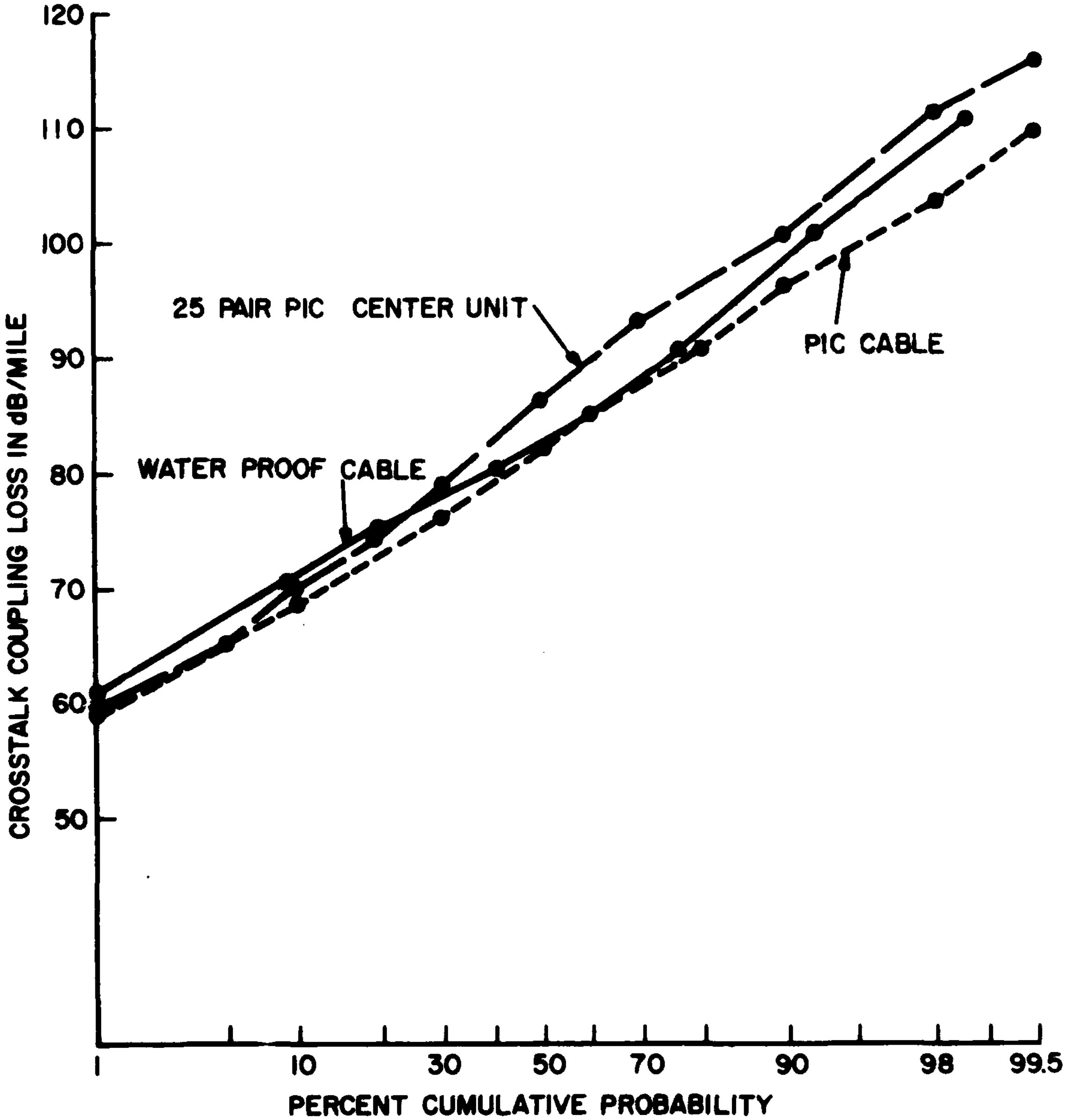


FIGURE 7
WATER PROOF CABLE FAR END CROSSTALK
150 kHz 25 PAIR,22 GAUGE

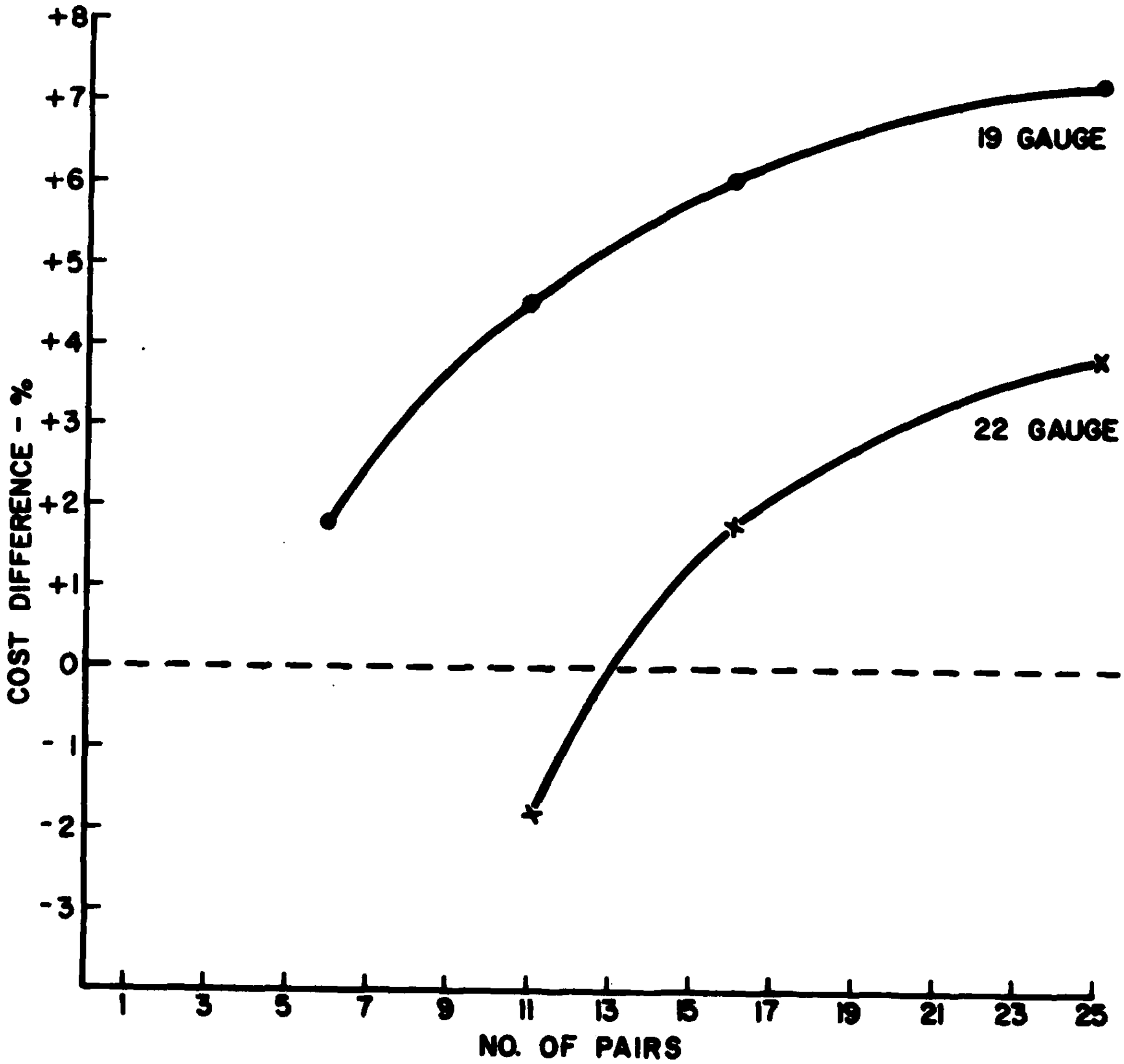


FIGURE 8
COST COMPARISON
PERCENTAGE COST INCREMENT OF WATERPROOF
CABLE OVER STANDARD PAP-PIC CABLE